# Systems Requirement Document
## for the
# Electron Beam Ion Source Project
# (EBIS)

**Project # 06-SC-002**

**at**
**Brookhaven National Laboratory**
**Upton, NY**

**For the U.S. Department of Energy**
**Office of Science**
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# 1 OVERVIEW

The EBIS Project provides a replacement for the Tandem Van de Graaff accelerators, the present heavy ion preinjector for RHIC, with a modern, reliable linac-based preinjector. This new preinjector will provide enhanced capabilities for both the RHIC and NSRL programs, at lower operating costs.

The project, including DOE and NASA contributions, includes the fabrication of an Electron Beam Ion Source for the production of high charge state heavy ions, plus the procurement of an RFQ and heavy ion Linac to accelerate ions from EBIS to a final energy of 2 MeV/amu. A transport line is to be fabricated to transport the beam from the output of the Linac to the existing Booster heavy ion injection point, as show below in Figure 1. The project includes the fabrication or procurement of the dipole and quadrupole magnets, power supplies, diagnostics, vacuum components, and controls to properly operate the EBIS source, accelerators, and beam lines. The project also includes the assembly of subsystems, and the installation and testing of these subsystems in their final location in the equipment bay at the high energy end of the H$^-$ Linac building.
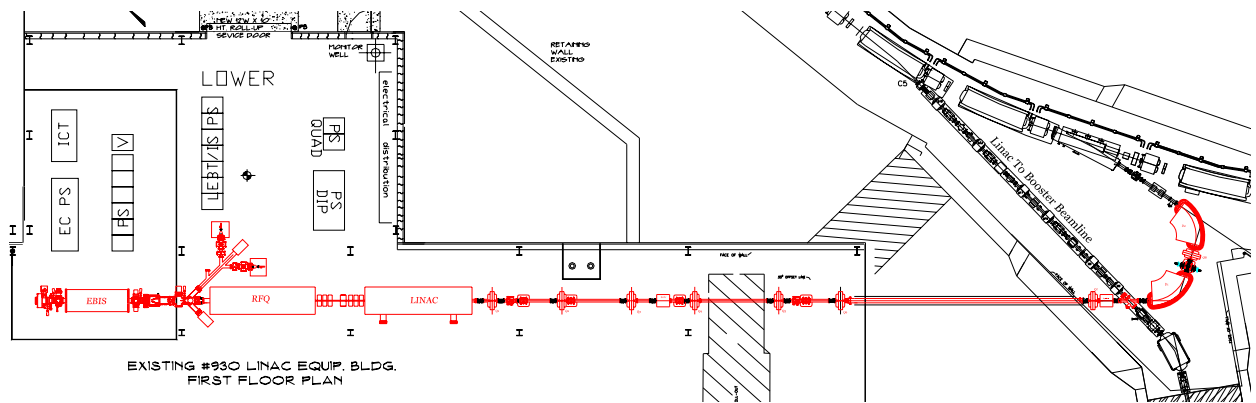


Figure 1  Layout of the EBIS Preinjector.

# 2 FUNCTIONAL REQUIREMENTS

The technical objectives of the new pre-injector need to meet requirements of both the RHIC and NASA NSRL experimental programs. The corresponding technical scope and performance specifications required at Critical Decision-4 (CD-4) are described in Table 2-2. The system parameters desired from a new pre-injector are as follows:

- **Species**: **d to U.** The EBIS source will produce helium to uranium beams. A deuterium beam may be produced in a simple plasma source injecting directly into the RFQ. The RFQ, Linac, and transport lines must be designed to handle all species in this range. The species extracted from EBIS depends on the injected singly charged ions. With the external ion sources included in the present design, beams from typical gases and solids as required by RHIC and NSRL will be available. Production of some more exotic beams may require additional development or resources devoted to the external source of such ions for injection.

- **Intensity at injection into the Booster: up to 1.1 x 10$^{11}$ charges/pulse with EBIS**. Species, which have been run for RHIC and NSRL, are shown in Table 2-1, along with intensities at Booster injection that are required in order to reproduce previously observed intensities. The EBIS pre-injector should at least match this performance in all cases.

Table 2-1  Beams and intensities at Booster input required to match past performance

| Species | User | Q | Ions/pulse | Charges/pulse |
|---------|------|-----|----------------------|----------------------|
| Au | RHIC | 32+ | $2.7 \times 10^9$ | $8.6 \times 10^{10}$ |
| D | RHIC | 1+ | $2.5 \times 10^{11}$ | $2.5 \times 10^{11}$ |
| Cu | RHIC | 11+ | $1.0 \times 10^{10}$ | $1.1 \times 10^{11}$ |
| C | NSRL | 5+ | $2.0 \times 10^{10}$ | $1.0 \times 10^{11}$ |
| O | NSRL | 8+ | $6.7 \times 10^9$ | $5.3 \times 10^{10}$ |
| Si | NSRL | 13+ | $5.0 \times 10^9$ | $6.5 \times 10^{10}$ |
| Ti | NSRL | 18+ | $1.3 \times 10^9$ | $2.4 \times 10^{10}$ |
| Fe | NSRL | 20+ | $1.7 \times 10^9$ | $3.4 \times 10^{10}$ |

- **Injected pulse width: variable, 10 – 40 μs.**  This allows 1-4 turn injection into the Booster.  This simplifies the injection, and should greatly reduce the sensitivity to beam losses at injection, which could otherwise lead to a pressure bump resulting in further beam loss.

- **Repetition rate: 5 Hz.**  This keeps overall RHIC fill times to only a few minutes.

- **Switching time between two species:  1 second**.  There are presently several operating scenarios for RHIC and NSRL, depending on, among other things, whether either is running alone, or the two are running concurrently.  To allow operation with the desired flexibility, the new pre-injector must be able to switch beam species and transport line rigidity in 1 second.

- **Injection energy: 2 MeV/amu.**  At present, injection from the Tandems is at 0.92 MeV/amu for Au.  At this energy, there is a significant beam loss due to electron capture during Booster injection.  By raising the injection energy to 2 MeV/amu, the capture cross section is reduced by a factor of 20-40.

- **Q/m: 0.16 or greater.**  This ratio equals that presently delivered for Au from the Tandem.  For lighter ions a higher q/m is required ($Si^{13+}$, $Fe^{20+}$) in order to achieve the desired Booster output energy for NSRL, within the rigidity constraints of the Booster and extraction transport lines.

Table 2-2  CD4 performance to be demonstrated at Booster input (measured on the current transformer located between the two HEBT 73 degree dipoles).

| | CD4 Performance | Optimum Performance |
|---|---|---|
| Species | Fe, Au | He to U (assuming appropriate external ion injection) |
| Intensity | $3 \times 10^8 \, Au^{32+}$ / pulse<br>$4 \times 10^8 \, Fe^{20+}$ / pulse | $2.7 \times 10^9 \, Au^{32+}$ / pulse<br>$4 \times 10^9 \, Fe^{20+}$ / pulse<br>$5 \times 10^{10} \, He^{2+}$ / pulse |
| Charge-to-mass ratio, Q/m | 0.162 (Au)<br>0.357 (Fe) | $\geq 0.16$, depending on ion species |
| Repetition rate | Demonstration of pulsing | 5 Hz |
| Pulse width | 10-40 μs | 10-40 μs |
| Switching time between species | Demonstration of switching | 1 second |
| Output energy | 2 MeV/amu | 2 MeV/amu |

# 3   SYSTEM REQUIREMENTS

All systems, which together comprise the EBIS-based RHIC preinjector, must be designed such that the functional requirements given in Section 2 are met.  In addition, the preinjector must do this while also ensuring reliability and maintainability. Performance requirements given in the following sections, when combined, will result in overall system performance that meets the functional requirements.  This overall performance of the entire system, using requirements given below, has been verified with beam optics simulations, including "end-to-end" simulations.  The subsystem requirements represent our present design, but may change with further optimization.

The approach taken to ensure reliability is to use proven technologies, and designs based on past experience within the accelerator community.  Whenever possible, we have chosen components and approaches that are the same as or similar to those used elsewhere in the RHIC accelerator complex, using standard components and designs.

## 3.1   ELECTRON BEAM ION SOURCE

The EBIS must produce ions of all desired species at the required charge state with sufficient intensity to meet the requirements for RHIC and NSRL.  Requirements for the EBIS source are given in Table 3-1.  These requirements are based on our past experience on a prototype EBIS source operating at BNL, plus well established scaling laws.  The final EBIS parameters are what we feel is an optimum combination that meets requirements for intensity, beam emittance, flexibility in production of ion species, and reliability, based on past experience and the experimental results of the prototype EBIS at BNL.  Other than a straightforward scaling of the length of the ion trap, the parameters chosen for the RHIC EBIS do not deviate in any significant way from those demonstrated in the very successful prototype EBIS.

Electron beam current and trap length are those required to produce the required ion charge.  Extraction voltage is chosen high enough to minimize space charge effects in the LEBT line, without being excessive, such that voltage holding and power supply requirements would become more difficult, and the RFQ length increase.

Table 3-1  EBIS Parameters

| Parameter | Value | Units |
|---|---|---|
| e-beam current | 10 | A |
| e-beam energy | 20 | keV |
| e-beam density | ~575 | A/cm$^2$ |
| Ion trap length | 1.5 | m |
| Trap capacity | 11 x 10$^{11}$ | charges |
| Yield positive charges, total | 5.5 x 10$^{11}$ | charges |
| Pulse length | 10 - 40 | µs |
| Yield Au$^{32+}$, design value | 3.4 x 10$^9$ | ions/pulse |
| Emittance (Au$^{32+}$, rms, normalized) | 0.035 | π mm mrad |
| Extraction energy | 17 | keV/u |

## 3.2   LEBT

The Low Energy Beam Transport (LEBT) transports the beam from the EBIS and matches it to the RFQ.  Table 3-2 shows the Twiss parameters at the beginning and end of the LEBT for Au$^{+32}$ with a kinetic energy of 17 keV/amu.  These are present parameters based on our nominal RFQ design, and could change somewhat once the RFQ detailed design is fixed.

Table 3-2  Twiss parameters at the beginning and end of the LEBT (Au$^{32+}$).

| Parameter | Beginning of LEBT | End of LEBT | Units |
|---|---|---|---|
| $\alpha_x$ | 0.0 | 1.057 | |
| $\beta_x$ | 0.075 | 0.0639 | mm/mrad |
| $\varepsilon_x$ (rms, normalized) | 0.035 | 0.09 | π mm mrad |
| $\alpha_y$ | 0.0 | 1.057 | |
| $\beta_y$ | 0.075 | 0.0639 | mm/mrad |
| $\varepsilon_y$ (rms, normalized) | 0.035 | 0.09 | π mm mrad |

## 3.3   RADIOFREQUENCY QUADRUPOLE ACCELERATOR (RFQ)

Preliminary performance requirements for the RFQ are given in Table 3-3.  The input energy is that required by space charge considerations in the injection line.  The general frequency range was driven by space charge considerations at the RFQ entrance, and within that range, the exact frequency was chosen to be one half the frequency of the present 200 MeV H- linac.  In this way, if one were to add additional accelerating cavities in the future, where the cavities would typically be at a higher frequency, one might use rf systems from the H- linac.  With these requirements, the RFQ is very similar to several existing and well proven RFQs.

Table 3-3  Preliminary RFQ Performance Requirements

| Parameter | Value | Units |
|---|---|---|
| Type | 4-rod | |
| Operating Frequency | 100.625 | MHz |
| Design Beam Current | 10 | mA |
| Maximum Beam Current | > 20 | mA |
| Charge-to-Mass (q/m) Ratio Range | 0.16 to 1.0 | |
| Repetition Rate, Max. | 5 | Hz |
| Pulse Width | $\leq 1.0$ | ms |
| Input Energy | 17.0 | keV/u |
| Input Emittance (rms, normalized, $Au^{32+}$) | 0.09 | π mm mrad |
| Acceptance (normalized) | $\geq 1.7$ | π mm mrad |
| Output Energy | 300 | keV/u |
| Emittance Growth | $\leq 20$ | % |
| Output Emittance, longitudinal (90%) | $\leq 172$ | π keV/u-deg |
| Transmission Efficiency | > 90 | % |
| Length | $\leq 4.4$ | m |
| Power (peak, no beam, q/m=0.16) | $\leq 180$ | kW |
| Tuning Range | $\geq 300$ | kHz |

## 3.4   MEBT

The purpose of the Medium Energy Beam Transport (MEBT) is to match the beam from the RFQ to the IH structure in all three planes (two transverse, and longitudinal). The RFQ has a FODO lattice with 1 βλ period and the IH structure has quadrupole triplet focusing.  The RFQ and the IH structure have the same RF frequency of 100.625 MHz. Table 3-4 shows the Twiss parameters at the output of the RFQ and input of the IH structure.

These parameters are based on preliminary RFQ and Linac designs, and could change once the final designs for these two structures are fixed.

Table 3-4 Twiss parameters at the end of the RFQ and entrance of the IH Linac ($Au^{32+}$).

| Parameter | End of RFQ | Entrance of IH | Units |
|---|---|---|---|
| $\alpha_x$ | 0.0 | 1.80221 | |
| $\beta_x$ | 1.0 | 1.01 | mm/mrad |
| $\varepsilon_x$ (rms, normalized) | 0.11 | 0.11 | $\pi$ mm mrad |
| $\alpha_y$ | 0.0 | 0.60246 | |
| $\beta_y$ | 0.05 | 0.59391 | mm/mrad |
| $\varepsilon_y$ (rms, normalized) | 0.11 | 0.11 | $\pi$ mm mrad |
| $\alpha_z$ | 0.054 | 0.37 | |
| $\beta_z$ | 0.0203 | 0.24 | deg/keV |
| $\varepsilon_z$ (90%) | 172 | 172 | $\pi$ keV/u-deg |

## 3.5   IH LINAC

Performance requirements for the linac are given in Table 3-5.  As with the RFQ, a design was chosen based on a proven technology and closely matching several existing linacs.

Table 3-5 Main parameters of the IH Linac

| Parameter | Value | Units |
|---|---|---|
| Operating Frequency | 100.625 | MHz |
| Design Beam Current | 5 | mA |
| Maximum Beam Current | > 10 | mA |
| Charge-to-Mass (q/m) Ratio Range | 0.16 to 1.0 | |
| Repetition Rate, Max. | 5 | Hz |
| Pulse Width | $\leq 1.0$ | ms |
| Input Energy | 300 | keV/u |
| Input Emittance (rms, normalized, $Au^{32+}$) | 0.11 | $\pi$ mm mrad |
| Input Emittance, longitudinal (90%) | 172 | $\pi$ keV/u-deg |
| Acceptance (normalized) | $\geq 4.3$ | $\pi$ mm mrad |
| Output Energy | 2000 | keV/u |
| Transverse Emittance Growth | $\leq 20$ | % |
| Longitudinal Emittance Growth | $\leq 25$ | % |
| $\Delta E$ (90%) for $Au^{+32}$ | $< \pm 10$ | keV/u |
| Transmission Efficiency | > 90 | % |
| Length | $\leq 4$ | m |
| Power (peak, no beam, q/m=0.16) | $\leq 125$ | kW |

## 3.6   HEBT

The High Energy Beam Transport (HEBT) matches beam transversely from the Linac to Booster injection, minimizes the energy spread at the injection, provides ion charge state discrimination, and provides space for diagnostics.  A beamline penetration through the Linac shielding provides a short, direct path into the Booster allowing injection using the existing heavy ion inflector.  Since the RFQ and Linac will not eliminate all unwanted charge states, the line will be designed for charge discrimination.  Two debuncher cavities will be used in HEBT to rotate the longitudinal phase space to minimize the energy spread at Booster injection.  Table 3-6 gives the Twiss parameters at the end of the Linac and entrance of the Booster for the mismatched injection scheme, for $Au^{32+}$. The parameters at the exit of the IH linac could change based on the linac design. Booster input parameters are based on the existing injection hardware and planned injection scheme.

Table 3-6 Twiss parameters at end of the IH Linac and entrance of the Booster for mismatch injection scheme ($Au^{32+}$).

| Parameters | End of IH Linac | Entrance to Booster | Units |
|---|---|---|---|
| $\alpha_x$ | 2.1 | -1.87 | |
| $\beta_x$ | 3.0 | 2.5 | mm/mrad |
| $\varepsilon_x$ (rms, normalized) | 0.14 | 0.14 | $\pi$ mm mrad |
| $\alpha_y$ | -1.59 | 0.87 | |
| $\beta_y$ | 3.45 | 4.8 | mm/mrad |
| $\varepsilon_y$ (rms, normalized) | 0.14 | 0.14 | $\pi$ mm mrad |
| $\Delta E$ (90%) for $Au^{+32}$ | ± 6.8 | ± 3.7 | keV/u |

## 3.7   DIAGNOSTICS

One must have appropriate types of diagnostics in sufficient number and at appropriate locations to allow the setup of the various beams and the monitoring of the source and preinjector performance during operations.  The location, number, and types of diagnostics have been verified through the development of a tune-up scenario.

| Device | Location and Quantity | | | | | Dyn. Range | Resolution | Comments |
|---|---|---|---|---|---|---|---|---|
| | EIL | LEBT | MEBT | HEBT | TOTL | | | |
| Current Transformer | | | | | | | | |
| Toroid | 1 | 2 | 1 | 3 | 7 | 10uA-10mA | 0.1 uA | Pulse |
| Faraday Cup | | | | | | | | |
| Fast Faraday Cup | | | | 1 | 1 | 10uA-10mA | 0.1 uA | Pulse |
| Faraday Cup | 2 | 1 | 1 | 2 | 6 | 10uA-10mA | 0.1 uA | Pulse |
| Profile Monitor | | | | | | | | Pulse |
| Multiwire | | 1 | | 2 | 3 | 10uA-10mA | 1 mm | 32H x 32V |

## 3.8    VACUUM

EBIS vacuum requirements are based on the extensive experience on the Test EBIS, where vacuum design features were key to the successful performance.  RFQ and Linac vacuum requirements are based on our experience with our present RFQ and linac.  The HEBT vacuum requirements are based on the vacuum requirements of the Tandem-to-Booster and Booster vacuum systems.

### 3.8.1    EBIS Vacuum

Ion confinement times as long as 100 ms may have to be used to reach the charge states of interest.  The background pressure in the trap region should be low enough that one does not produce a significant number of ions from the background gas.  For a residual gas pressure $P=1\times10^{-10}$ Torr, one estimates that less than 2% of the accumulated ions in the trap will be background gas ions.  One can tolerate values even a factor of 10 above this, so this gives a range of acceptable vacuum conditions in EBIS of $10^{-9} - 10^{-10}$ Torr.  Requirements for the concentration of hydrogen are less rigorous, and its partial pressure can be 5 times higher.  Requirements on the pressure of residual gas in the electron gun region are dictated primarily by the need for proper conditions for operation of the cathode, and in the electron collector by the need for stable transmission of the electron beam without plasma formation.  Normally, the pressure in the regions of electron gun and electron collector can be higher than in the ionization region, provided there is efficient vacuum separation between the sections.

### 3.8.2    RFQ, MEBT, and Linac

The fully assembled RFQ and Linac shall be designed to achieve vacuum levels of $7.5 \times 10^{-8}$ Torr without RF power and $2 \times 10^{-7}$ Torr with RF power.  A similar vacuum level is sufficient for the short, connecting MEBT line.

### 3.8.3    HEBT

Vacuum levels of $10^{-8}$ and $10^{-9}$ Torr are sufficiently low for the partially stripped low energy ion beams for most of HEBT, due to the single pass nature, except at the downstream end. Vacuum of $10^{-10}$ Torr is needed in the last section of HEBT to minimize the diffusion of residual gas into the $10^{-11}$ to $10^{-12}$ Torr Booster ultrahigh vacuum system.

## 3.9    ALIGNMENT

Alignment tolerances for the MEBT and HEBT magnets is given in Table 3-7.

Table 3-7 Alignment Tolerances

| Type of Error | Tolerance | Units |
|---|---|---|
| Translation (x and y) | +/- 0.1 | mm |
| Pitch and yaw | +/- 1 | mrad |
| Rotation | +/- 0.5 | deg |

## 3.10  SAFETY

The EBIS preinjector and all its components must comply with all laboratory safety requirements.  Equipment must undergo design and safety reviews and have all required approvals prior to operation.  Detailed environmental, safety and health requirements are given in the Hazard Analysis Document.

### 3.10.1   Radiation

There must be sufficient shielding, or personnel access must be limited on the Linac side of the beam penetration in to the Booster.  X-ray levels from RF cavities must be shielded, or access limited, as appropriate.  Two independent, failsafe methods must be provided for keeping beam from entering the Booster.  All radiological work will comply with requirements in the BNL Radiological Control Manual.

### 3.10.2  Electrical

All electrical equipment must be certified by a Nationally Recognized Testing Laboratory, or be approved for use by the local authority having jurisdiction.  All high voltages must be proper barriered.  All equipment must be properly grounded.  All electrical work must be performed by trained and qualified staff, and all staff, including supervisors and Group Leaders, will help ensure the use of personal protective equipment by workers.

### 3.10.3  Cryogenic / Oxygen Deficiency Hazards

The EBIS superconducting solenoid must undergo the required Cryogenic Safety Committee reviews, which will verify appropriate pressure relief devices, pressure vessel certifications, etc.  There should be appropriate venting of gasses such that the EBIS area does not exceed ODH-0 classification, which is a BNL standard.

### 3.10.4  Environmental

All oils must be non-PCB, and must have appropriate containment, dependent on the volume of oil.  An environmental process assessment must be performed prior to operations to determine inputs and outputs, waste minimization opportunities and applicable requirements.